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Mathematical Model to Study Solar Cookers Box-Type with Internal Reflectors

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Abstract

A mathematical model to determine the thermal function on a solar cooker box-type with internal reflector as well as one application in numerical simulation for predicting the transitory thermal behavior are shown.
The mathematical model validation is carried out when numerical results generated by numeric simulation are compared versus own experimental results and experimental results reported by El-Sabaii and Domanski at Tanta, Egypt. Experimental data obtained by El-Sabaii and Domanski were selected because these were obtained under controlled conditions and their solar cooker prototype is similar to the solar cooker analyzed in this work.
For the mathematical model solution, ambient temperature and solar radiation values were used and for this purpose, experimental data were obtained. A device Compact Field Point Model FP-TB-3 to obtain ambient temperature values was used and an Eppley piranometer 8-48 for obtaining solar radiation data was used. The information obtained was processed using the Labview software of National Instruments.
A case when the solar cooker is integrated for 3, 4 and 5 steps is considered and the thermal behavior in the solar cooker for this case is evaluated.
The main results allow to explain how the increment in the internal steps impacts on the temperatures in the solar cooker.
Also is explained how the mathematical model can be used for different applications as different fluids and different liquid amounts.
Finally, is pointed out how the numerical techniques can be useful to analyze solar devices as solar cookers box-type.

Keywords: Solar cooker box-type, internal reflector, internal steps, temperature, radiation

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1. Introduction

There are many opinions about how solar energy can be applied to domestic uses; some of them indicate that solar cookers may be one such case. Investigators around the world have developed several types of solar cookers; among those one can be found the box-type, with flat plate or with concentrator.

Due to their easy construction and low cost, the box-type solar cooker has been studied and improved for years. One improvement for this solar cooker has been to add internal reflectors, also called multi-step inner reflectors which have turned out a practical successful.

Nomenclature

Q	Heat flow (W)
A	Area (m^2)
h	heat transfer convection coefficient (W/ m^2 K)
T	Temperature (K)
m	Mass (kg)
t	Time (sec)
SRK:	Step in the Runge-Kutta method
C	Specific heat (kJ/kg K)
G	Incidental solar radiation (W/m^2)
Subindex	
g	Glass
r	Reflector
c	Sky
f	Fluid
amb	Ambient
e	Mirror
ref	Reflector
fs	Upper fluid
m	Wet
t	Lid
int-1	Inner 1
int-2	Inner 2
int-3	Inner 3
Greek letters	
σ	Steffan-Boltzman constant (5.669X10^{-8} W/m^2 K^4)
ρ	Reflectivity
ε	Emittance
α	Absorptance
Θ	Reflector angle
τ	Transmittivity

Authors as Group, et. al. [1] have investigated solar cookers box-type, their results have been useful as reference to other investigations. Among their investigations, they have showed a numerical simulation for a solar cooker box-type, their results were applied to determine the effects in the absorbent and the pot, as well as the thermal behaviour in the conductivity of the absorbent. At Tanta, Egypt, El-Sebaii and

Domanski [2] obtained analytical expressions to determine temperatures in a solar cooker in several parts in the same one. With those results they determined their thermal behaviour. In another work presented by Thulasi et al. [3] they obtained a mathematical model for a solar cooker box-type and they exposed problems for a great quantity of parameters that participate in the thermal operation of solar cookers. A parametrical model for the operation in a solar cooker to predict their cooking power was presented by Funk and Larson [4]. The model was based on three controlled parameters (area of solar interception, overall heat loss coefficient, and thermal conductivity of the plateful base's absorber) and three not controlled variables (heatstroke, temperature difference, and load distribution). This model was validated using solar commercial cookers. Kariuki et al. [5] applied finite-differences to obtain the numerical simulations in a pot with cold water. The pot was placed on a hot storage block and the time was estimated until the water had boiled or the temperature in the water had reached a maximum value. For a given capacity in a pot, numerical simulations were made; the storage block was made in cast iron and granite (rock). Thermal behaviour for different ratios heights-diameters and sizes in the solar zone area input were obtained. Pejack [6] developed a mathematical model considering the heat transfer processes for a solar cooker box-type, containing foods. Solar radiation and a flat reflector over the box were considered. Small time increments were evaluated. The computer model finds temperatures of air, food, interior walls and top cover. In the results obtained, the solar flux throughout the cooking period was considered. Some of sample results were presented. He showed how the food temperature is affected by latitude, month, wind, clouds, mass of food and thermal resistance of the box walls and adjustment of the box while cooking. Suharta et al. [7] described the influences which govern to the solar box cookers and they proposed a new design. Results obtained for them, showed that the best of solar cookers, gave a cooking temperature of 202°C between 12:00 and 12:45 p.m. on October 7, 1997. It was found that this solar cooker has a good heat storage capability; therefore it can be used for consecutive cooking. The size optimization, the aperture area, the insulator thickness, the oven volume and the reflector area lead to a new design called HS 5521 were presented. Its volume is only 35% of the volume of first model, and it is cheaper to manufacture. Kumar, S. [8], presented a simple test procedure to determine design parameters to predict the thermal performance in a solar cooker box-type. An out-door series experiments were performed on the double-glazed solar cooker with aperture area 0.24 m^2 to obtain two figures of merit, F1 and F2. The proposed procedure is then applied to predict the heating characteristic curves in the solar cooker with different load of water. Terres and Quinto [9] presented the numerical results when a box type solar cooker with inner reflectors was evaluated in two cases of application. The first of them was a comparative with a previous design made in Tanta, Egypt, and the second one was a numerical test for long time operation (10 hours). El-Sebah, [10] presented a simple mathematical model for a box-type solar cooker with outer-inner reflectors. It is based on analytical solution of the energy-balance equations for different elements of the cooker. The cooker performance is investigated by computer simulation in terms of the cooker efficiency as well as characteristic and specific boiling times. El-Sebaii and Aboul-Enein [11] presented a transient mathematical model for a box-type solar cooker with a one-step outer reflector hinged at the top of the cooker. It is based on analytical solution of the energy-balance equations using Cramer's rule for different elements of the cooker. Various heat-transfer coefficients are assumed to be temperature dependent. Terres et al. [12] they presented a second law analysis applied to a solar cooker box-type with multi-step inner reflectors. By second law efficiency concept, the real yield of this cooker type was shown. The result of the analysis shows that the yield of the solar cooker under transitory operation conditions is smaller than 5% and this result added to the construction costs, allows a real evaluation of this type of solar cooker. In this work, the validation for a mathematical model as well as one application to determine the thermal function in a solar cooker box-type with variables steps are shown. The validation is made using water as test fluid. Also one application case is analysed when the inner-steps in the cooker are evaluated for 3, 4 and 5 steps. In figures 1 and 2, the solar cooker prototype and an illustrative scheme are shown. The results obtained can be useful for design proposes and the mathematical model can be considered as a versatile contribution to develop or improvement other models and to determine the thermal behaviour in solar cookers box-type with internal reflectors.

Fig. 1 Solar cooker box type prototype

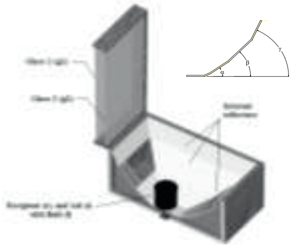

Fig. 2 Solar cooker box type illustrative scheme

2. Mathematical model and numeric solution

The solar cooker with internal reflectors is integrated by the following elements: 1. a cover with two flat glasses with a clearance between them. 2. Internal reflectors made in commercial aluminium paper placed to different tilt angles, 3. Thermal insulator placed in the lateral part of the same one, and 4. Recipient contains the product to cook. The solar cooker is locked air tightly; this allows reaching considerable temperatures in the test fluid, which is water for this study. The mathematical model used in the numerical simulation takes in account gains and losses of energy for each component of the cooker. The energy balance in the solar cooker is shown in figure 3. The energy balances are applied to a) glass 1, b) glass 2, c) lid, d) recipient and e) fluid.

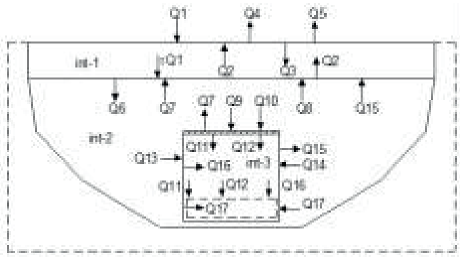

Fig. 3 Heat flows in the solar cooker

a) Balance of energy for glass 1. $m_{g1} c_{g1} \dfrac{dT_{g1}}{dt} = Q_1 + Q_2 - Q_3 - Q_4 - Q_5$ (1)

$Q_1 = A_{g1} G \alpha_{g1}$ Solar radiation over glass 1

$Q_2 = \dfrac{A_{g1}\sigma(T_{g2}^4 - T_{g1}^4)}{\dfrac{1}{\varepsilon_{g1}} + \dfrac{1}{\varepsilon_{g2}} - 1}$ Heat flow radiation of glass 2 toward glass 1

$Q_3 = A_{g2} h_{g1-\mathrm{int}1}(T_{g2} - T_{g1})$ Heat flow convection of glass 1 toward the inner 1

$Q_4 = A_{g1}\sigma\varepsilon_g (T_{g1}^4 - T_c^4)$ Heat flow radiation of glass 1 toward the sky

$Q_5 = A_{g1} h_{g1-amb}(T_{g1} - T_{amb})$ Heat flow convection of glass 1 toward the ambient

b) Balance of energy for glass 2. $m_{g2}\, c_{g2}\, \dfrac{dT_{g2}}{dt} = \tau_g Q_1 - Q_2 - Q_6 + Q_7 + Q_8 + Q_{15}$ (2)

$Q_6 = A_{g2} h_{g2-\text{int}1}(T_{g2} - T_{g1})$ Heat flow convection of glass 2 toward the inner 1

$Q_7 = A_{tapa}\sigma\varepsilon_{tapa}(T_t^4 - T_{g2}^4)$ Heat flow radiation from the recipient lid toward glass 2

$Q_8 = A_{g2} h_{g2-\text{int}2}(T_{\text{int}2} - T_{g2})$ Heat flow convection of the inner 2 toward glass 2

$Q_{15} = A_r\sigma\varepsilon_r(T_r^4 - T_{g2}^4)$ Heat flow radiation of recipient toward glass 2

c) Balance of energy in the lid of the recipient. $m_t\, c_t\, \dfrac{dT_t}{dt} = -Q_7 + Q_9 + Q_{10} - Q_{11} - Q_{12}$ (3)

$Q_9 = A_t h_{t-\text{int}2}(T_t - T_{\text{int}2})$ Heat flow convection of inner 2 toward the lid

$Q_{10} = A_t G \tau_g^2 \alpha_t$ Heat flow radiation for the sun and absorbed by the lid

$Q_{11} = A_t h_{t-\text{int}3}(T_t - T_f)$ Heat flow convection of the lid toward the inner 3

$Q_{12} = A_t\sigma\varepsilon_t(T_t^4 - T_f^4)$ Heat flow radiation of the lid of the recipient toward the fluid

d) Balance of energy on the recipient. $m_r\, c_r\, \dfrac{dT_r}{dt} = Q_{13} + 4Q_{14} - Q_{15} - Q_{16} - Q_{17}$ (4)

$Q_{13} = A_r h_{r-\text{int}2}(T_{\text{int}2} - T_r)$ Heat flow convection of recipient to the inner 2

$Q_{14} = \sum_{i=1}^{n} \rho A_{ref,n} G \tau_g^2 \cos(90 - \theta_{ref,n})$ Heat flow reflection of incident radiation on the reflectors (with n = number of reflectors)

$Q_{16} = A_r\sigma\varepsilon_r(T_r^4 - T_f^4)$ Heat flow radiation of recipient toward the fluid

$Q_{17} = A_m h_{r-Am}(T_r - T_f)$ Heat flow convection of recipient toward the fluid

e) Energy balance for the fluid. $m_f\, c_f\, \dfrac{dT_f}{dt} = Q_{11} + Q_{12} + Q_{16} + Q_{17}$ (5)

By placing the heat flow terms into the equations (1) to (5), the mathematical model can be expressed in an explicit way:

$$m_g\, c_g\, \frac{dT_{g1}}{dt} = A_g G \alpha_g + \frac{A_g\sigma\varepsilon_g(T_{g2}^4 - T_{g1}^4)}{\dfrac{1}{\varepsilon_{g1}} + \dfrac{1}{\varepsilon_{g2}} - 1} - A_g h_{,g1-\text{int}1}(T_{g2} - T_{g1}) - A_g\sigma\varepsilon_g\left(T_{g1}^4 - \left(0.0552 T_{amb}^{1.5}\right)\right) - A_g h_{g1-amb}(T_{g1} - T_{amb}) \tag{6}$$

$$m_g\, c_g\, \frac{dT_{g2}}{dt} = \tau_g A_g G \alpha_g - \frac{A_g\sigma\varepsilon_g(T_{g2}^4 - T_{g1}^4)}{\dfrac{1}{\varepsilon_{g1}} + \dfrac{1}{\varepsilon_{g2}} - 1} - A_g h_{g2-\text{int}1}(T_{g2} - T_{g1}) + A_t\sigma\varepsilon_t(T_t^4 - T_{g2}^4) + A_g h_{g2-\text{int}2}\left[\frac{T_{g2} + T_t + T_r}{3} - T_{g2}\right] + A_r\sigma\varepsilon_r(T_r^4 - T_{g2}^4) \tag{7}$$

$$m_t\, c_t\, \frac{dT_t}{dt} = -A_t\sigma\varepsilon_t(T_t^4 - T_{g2}^4) + A_t h_{t-\text{int}2}(T_t - T_{\text{int}2}) + A_t G \tau_g^2 \alpha_t - A_t h_{t-\text{int}3}(T_t - T_f) - A_t\sigma\varepsilon_t(T_t^4 - T_f^4) \tag{8}$$

$$m_r c_r \frac{dT_r}{dt} = A_r h_{t-\mathrm{int}2}\left[\frac{T_{g2}+T_t+T_r}{3}\right] + 4\sum_{i=1}^{n}\rho A_{ref,n} G\tau_g^2 \cos(90-\theta_{ref,n}) - A_r\sigma\varepsilon_r\left(T_r^4 - T_{g2}^4\right) - A_r\sigma\varepsilon_r\left(T_r^4 - T_f^4\right) - A_m h_{r-fl}\left(T_r - T_f\right) \quad (9)$$

$$m_f c_f \frac{dT_f}{dt} = A_t h_{t-\mathrm{int}3}(T_t - T_f) + A_t\sigma\varepsilon_t(T_t^4 - T_f^4) + A_r\sigma\varepsilon_r(T_r^4 - T_f^4) + A_m h_{r-fl}(T_r - T_f) \quad (10)$$

The function that relates number of reflectors and its reflection angles has been included in equation (9). These equations have been simplified by means of the following considerations:

i) The temperature T_c in Q_4 can be calculated by means of the correlation given by Swinbank [13]

$$T_c = 0.0552 T_{amb}^{1.5} \quad (11)$$

ii) The temperature T_{int2} in Q_8 and Q_{13} are obtained in function of others temperatures by means of the following supposition:

$$T_{\mathrm{int}2} = \frac{T_{v2}+T_t+T_r}{3} \quad (12)$$

iii) Properties: absortivity (α), reflectivity (ρ) and transmisivity (τ) have been considered constant.

iv) Heat convection coefficients have been estimated of data given by Thulasi, et al. [3].

v) The solar radiation impact over the solar cooker occurs in perpendicular way.

The mathematical model has been solved by means of the fourth order Runge Kutta's method. This solution was possible through the use of software developed in C++, which allows evaluating different cases of application for box type solar cookers with internal reflectors. By using experimental data of solar radiation and ambient temperature as well as solar cooker geometry, it is possible to determine the distribution of temperature for different parts in the same one. The experimental data are useful because it diminishes the difference between experimental and numerical values. The flowchart corresponding to the applied method is shown in fig. 4.

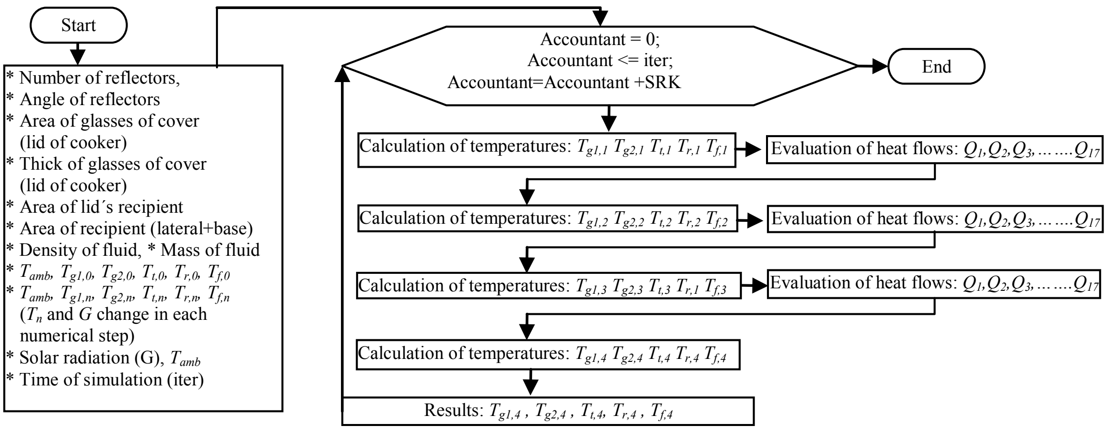

Fig. 4 Runge Kutta Method flowchart.

3. Mathematical model validation

In the mathematical model validation, the numerical results were generated by means of a software developed in C++. These were compared with own results and experimental data obtained by El–Sebaii and Domanski. The experimental data obtained by El-Sabaii were selected because these were obtained under controlled operation conditions. The average values for ambient temperature and solar radiation used in their experimental tests were 34.5 °C and 476 W/m² respectively. These values were considered as constant in that study. However, the mathematical model development in this paper allows generating numerical solutions when the solar radiation and ambient temperature are constant or variable. The experimental data in this work was acquired using an Eppley piranometer Model 8-48 and a Field Point Model FP-TB-3 device. Due to the experimental data obtained be El–Sebaii and Domanski were generated in a laboratory; the time for the warm-up process was short, as one view in the figures 5 to 9. Water was used both as test fluid in the experimental tests but, it is important to point out that the mathematical model allows considering different liquids if it is necessary. The geometrical description as well as conditions for the water quantity used is shown in table A1, Appendix. As one can see in figures 5 to 9, the numerical results obtained by simulation compared with own results have the smallest differences while the biggest differences happen for the comparative with the numerical results reported by El–Sebaii and Domanski. The maximum differences are 26.4% in T_r, (fig. 8) and 7.6 % in T_g, (fig. 6). These differences happened when the tests are starting; in this case the reason in the differences can be associated to the convergence´s method which is minor for the final data. The glass 1 is where the solar cooker is more exposed to the exterior effects such as heat convection. The cooker could be influenced by wind velocity, and the heat radiation interchange between the surrounding and the solar cooker. Another possible explanation between experimental and numerical result differences can be associated to the loss of heat in the mathematical model developed for the solar cooker, which might have taken in account more losses than really happen in the experimental tests. According to the values, it is possible to establish that the mathematical model and their results can be useful to predict the tendency of the temperature values in the solar cooker well. So, the numerical data for the temperatures will give a good behavior and description for the solar cooker. The comparisons of simulated and experimental values for water are shown in figures 5 to 9. In figure 10, the experimental data used in the simulation are shown. These were selected about 10 different experiments done. In these data were sought the best tendency in the same one. According to the data, their behavior shows an acceptable adjust, useful such as conventional measures for the numerical simulation.

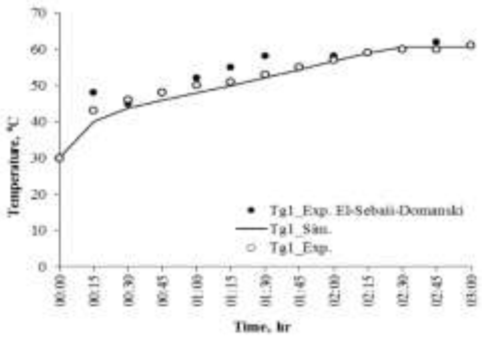

Fig. 5 Experimental and numerical results: T_{g1}

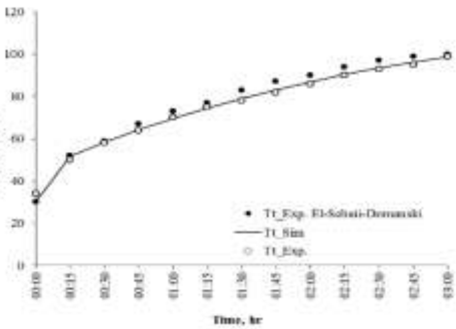

Fig. 7 Experimental and numerical results: T_t

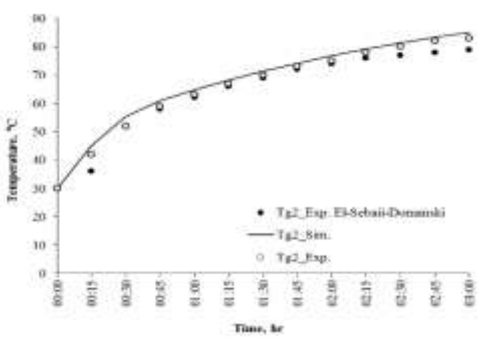

Fig. 6 Experimental and numerical results: T_{g2}

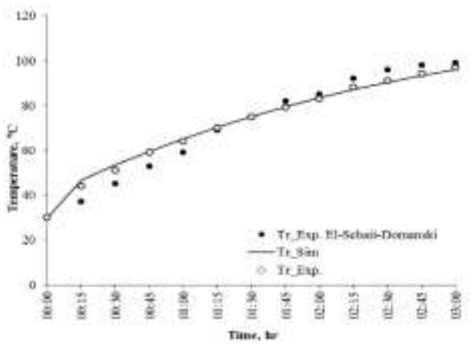

Fig. 8 Experimental and numerical results: T_r

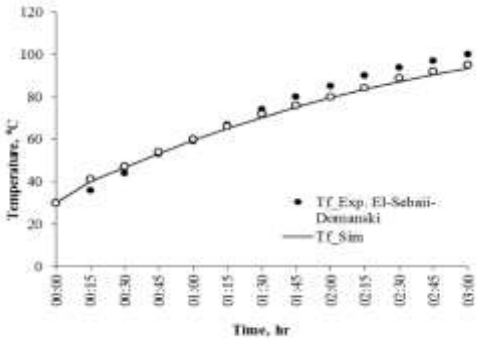

Fig. 9 Experimental and numerical results: T_f

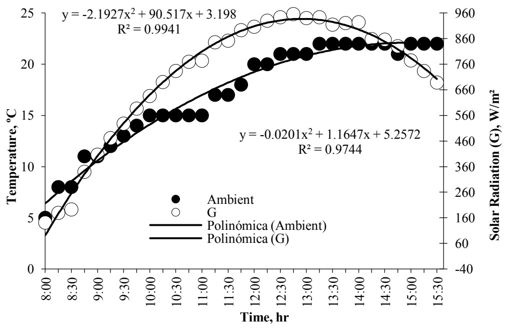

Fig. 10 Experimental data used in the simulation

4. Application of the mathematical model: Variable internal step

To illustrate an application for the mathematical model, three different arrangements for the solar cooker box-type were considered. These are 3, 4 and 5 steps. In table A2 (Appendix) their dimensions are shown. According to the mathematical model, in the numerical simulation solar radiation and environment temperature are necessary. For this reason, experimental data were used. These values were obtained for December at Mexico City. In the experimental process to obtain the values were used an Eppley piranometer Model 8-48 and a Field Point Model FP-TB-3 device. These data were used as initial numerical conditions in the simulation. The information acquired was processed with the LabView software. The convection coefficients values utilized in the mathematical model for the case analyzed in the solar cooker have been estimated according to the data from Thulasi et al. [3]. These values with other parameters were $h_{g1\text{-}amb} = 13.3$ W/m^2 K, $h_{g1\text{-}int1} = 3.8$ W/m^2 K, $h_{g2\text{-}int2} = 4.4$ W/m^2 K, $h_{r\text{-}int2} = 4.4$ W/m^2 K, $h_{t\text{-}int2} = 4.4$ W/m^2 K, $h_{t\text{-}int3} = 4.0$ W/m^2 K, $h_{f\text{-}int3} = 4.0$ W/m^2 K, $h_{r\text{-}Am} = 4.0$ W/m^2 K, $m_t = 0.1$ kg, $\rho_g = 2730$ kg/m^3, $\rho_{water} = 1000$ kg/m^3, $C_g = 800$ J/kg-K, $C_t = 900$ J/kg-K, $C_r = 900$ J/kg-K, $C_f = 4190$ J/kg-K, $\varepsilon_g = 0.35$, $\varepsilon_t = 0.85$, $\alpha_g = 0.17$, $\alpha_r = 0.9$, $\alpha_t = 0.9$, $\alpha_e = 0.5$, $\tau_g = 0.48$. The maximum temperatures to water for 3, 4 and 5 internal steps are 95.9, 100.7 and 106.2 ºC respectively, as one can see in figures 10 to 12. A comparison for the temperature water for the cases considered is shown in figure 13.

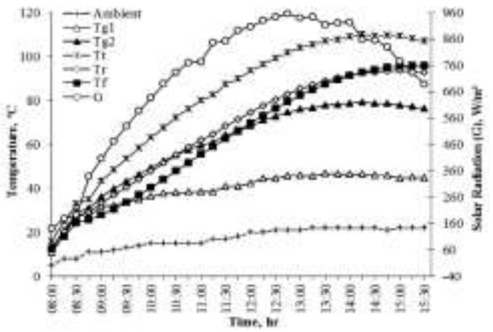

Fig. 10 Solar box cooker: 3 internal steps

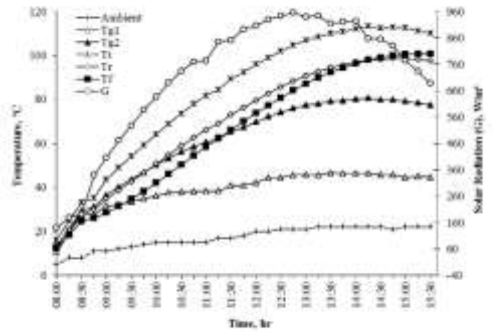

Fig. 11 Solar box cooker: 4 internal steps

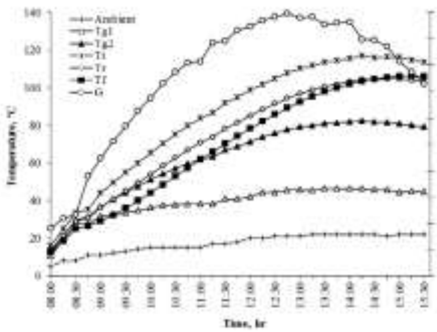

Fig. 12 Solar box cooker: 5 internal steps

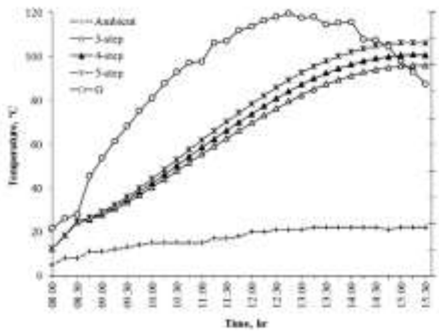

Fig. 13 Solar box cooker: Comparative for fluid (water) temperature

6. Discussion

As one can see in figures 10 to 13 the maximum temperature for the cooker occurs in the lid for the three cases. It happens because the lid is exposed to the direct solar radiation and effects of the inner convection in the cooker. The minimum temperature occurs for the glass 1, which is placed in contact with the ambient temperature and it is affected for the exterior convection. The maximum temperatures for water are 95.9, 100.7 and 106.2 °C and correspond to 3, 4 y 5 steps respectively. According to results, the solar cooker reaches the highest temperature with 5 internal steps, while the smallest temperature increase occurs with 3 internal steps. This can be explained by the increase of reflection area which, when the internal step is increased, the reflection area increases also. Besides, when the internal step number is increased, the body temperature on the recipient also increases, this explains the temperature increase in the water.

7. Conclusions

The increment in the steps in the solar cooker box-type was analyzed. When the steps are increased, the inside temperatures in the solar cooker also will increase. The increase in the number of steps allows reaching the highest temperature for water (106.2 ºC). According to reached temperatures, this kind of cooker can be used to baking and to warm-up of conventional foods. The study done in this work allows defining the adequate features in a solar cooker according to his sizes and variants, and to select the appropriate design according to the required need. Another important factor that intervenes in the heating fluid process is the specific heat as well as the density of the fluid. For other fluids different to water, the heating process will be different, which allows extending the coverage of this type of solar cooker. Other applications for the mathematical model can be the study of the thermal behavior for the solar cooker when the thicknesses in glasses are varied, the clearance between glasses, or the use of liquids different to water. The numeric procedure exposed in this work can be useful to study the thermal behavior in solar cookers box-type, and this information can be needed for new designs. Finally, this numeric analysis can avoid building many physical devices and this would allow to save money and research time.

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Appendix

Table A1 Geometrical dimension for a solar cooker: Validation

Seps	Reflector	Reflector degree	A_{ref} m^2	$A_{g1} = A_{g2}$ m^2	Thickness $_{g1} = _{g2}$ m	A_t m^2	A_r (lat.+base) m^2	m_f kg
	1	30	0.0058					
3	2	45	0.0530	0.4761	0.005	0.0201	0.0804	1.5
	3	75	0.0544					

Table A2 Geometrical dimension for solar cookers: Variable Steps

Steps	Reflector	degree	A_{ref} m^2	$A_{g1} = A_{g2}$ m^2	Thickness $_{g1} = _{g2}$ m	A_t m^2	A_r (lat.+base) m^2	m_f kg
	α	40	0.0391					
3	β	50	0.0532	0.4856	0.005	0.0314	0.0942	2
	γ	60	0.0646					
	α	40	0.0391					
	β	50	0.0532					
4	γ	60	0.0646	0.5856	0.005	0.0314	0.0942	2
	ϕ	70	0.0731					
	α	40	0.0391					
	β	50	0.0532					
5	γ	60	0.0646	0.64	0.005	0.0314	0.0942	2
	ϕ	70	0.0731					
	θ	80	0.0782					